SMALL ALTERNATING CURRENT MOTORS

by
ALFRED H. AVERY
A.M.I.E.E.

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Selection, Winding & Self-Starting

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SMALL ALTERNATING CURRENT MOTORS

A practical handbook describing types, running characteristics, starting arrangements and the general applications of fractional horse-power alternating current motors, with rules for the estimation of new windings

BY

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Author of

"A B C of Dynamo Design," "Fractional Horse-power Motors," "Small Transformers," etc., etc.

Fully Illustrated

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INTRODUCTION

THE subject of small A.C. motors is one upon which there is an almost complete absence of practical literature at present. It is one, moreover, that is becoming of increased interest to the model maker and home worker, since he is largely dependent upon fractional horse-power alternating current motors for workshop and domestic use, now that alternating current services are being so much extended in place of direct current supplies.

In the following notes sufficient information will be found to enable the different types of motors to be recognised, and their characteristics are explained in sufficient detail to enable anyone previously unfamiliar with their habits to choose the kind of motor best suited for the work it is required to do.

A special feature is that for the first time an attempt has been made to meet a want long experienced, by formulating a few simple rules for the calculation of windings to suit changed conditions of voltage, frequency, or speed. Especial attention has been given to the important question of self-starting, which is always one of the problems peculiar to single-phase motors.

Small A.C. motors are almost invariably limited to use on single-phase circuits at voltages customary for lighting purposes. Even when three-phase current is available, they are generally connected to one "leg" of the supply, for the reason that it is difficult to provide adequate insulation in such small frames as would comply with the safety requirements for voltages commonly used on three-phase power circuits.

The photographic illustrations used in this book have been contributed by the British Thomson-Houston Co. Ltd., of Rugby, to whom the fullest acknowledgments are due for their ready assistance. The quality of B.T.-H. products is well known ; the details are typical of modern practice in almost any make of motor.

A. H. Avery.

SMALL ALTERNATING CURRENT MOTORS

CHAPTER I
TYPES AND CHARACTERISTICS

Not so many years ago motors of the direct current type held the field almost exclusively for small power drives. The D.C. motor was a well-designed and well-constructed article, the outcome of many years of experimental development, and its general details were more or less familiar to all engineers. The small alternating current motor, on the other hand, was looked at with suspicion, and in many instances one is forced to admit with more than a little justification. Designs at that time were inefficient; the motors were generally very noisy, they frequently broke down, they were bad starters, and in fact were generally unpopular, both with consumers and supply companies alike. The excessive current they took to start them up caused disturbances on the line, and fuses of such dimensions had to be put in to withstand these heavy starting currents that they afforded practically no protection at all to the motor when once it got running.

The changing conditions of late years have extended public electric supply to a vastly greater number of towns and villages throughout the country. Efficient transmission on this scale can only be accomplished by alternating current, consequently a public supply of A.C. is now practically universal, while direct current supply is exceptional. This

has stimulated the efforts of our motor designers to such a point that the small alternating current motor of the present day is in every way as efficient and reliable as its direct current counterpart ; indeed in some respects it is superior.

In spite of this development, however, the A.C. motor has not become so familiar to the general public, so far as its principles and operating characteristics are concerned, as the older D.C. types, and very little has apparently been done to bridge this gap in the way of semi-technical literature. An effort to meet this deficiency is made in this book.

Perhaps it is scarcely surprising that so many people who use A.C. motors are unfamiliar with their internal details, for the almost universal practice latterly has been to build small motors for all commercial purposes, whether A.C. or D.C., with end frames of the " enclosed " or " protected " type. This makes it practically impossible to get any view of the inside construction without first opening up the machine. And, as many an amateur has found to his cost, attempts to do so have often resulted in considerable damage being done, or else incorrect reassembly, either result leading to an ignominious return of the machine to its makers to be put right again.

There is scarcely any difference externally in the appearance of either D.C. or A.C. small motors. Many firms in fact make a selling point of interchangeability as regards overall dimensions, fixing holes, shaft centre height, etc., whether the motor is for operating on direct or on alternating current, so that it is only by viewing the internal details that the one can be distinguished from the other. Fig. 1, for instance, is representative of the general likeness which exists between all modern totally enclosed motors, whether for alternating or direct current. It is little to be wondered at, therefore, if the amateur should look askance at problems involving any overhaul or rewinding.

Before one can deal intelligently with matters relating to rewinds or repairs, it is absolutely necessary to be able to

differentiate between the various types of small A.C. motors in use. Their speed characteristics and starting torques must also receive due attention, since a great deal lies in the choice of a type of motor suited to a particular purpose. Certain jobs require, for instance, a heavy starting torque

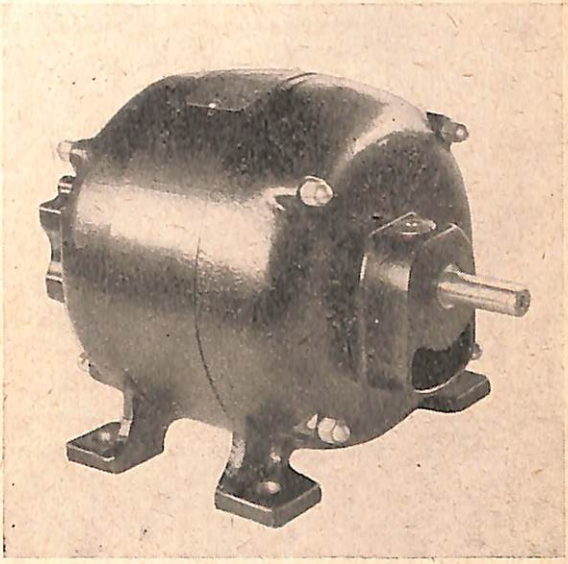

Fig. 1.—External view of small a.c. or d.c. motor

to overcome the frictional resistance or inertia of the moving parts. Line shafting in the workshop is a case in point; reciprocating pumps is another. Both these may require a starting torque far in excess of the normal running torque. Direct-driven fans, small grinding wheels, high-speed drills, etc., where there is no initial load beyond bearing friction, and no applied load until full speed has been attained, only call for a relatively small starting effort. Obviously, then, it is useful to be able to classify A.C. motors according to the starting torque they can develop.

Speed and Torque

A classification of small A.C. motors according to their speed and torque characteristics is given in the following table, in which has been included also the respective starting currents expressed as a percentage of the normal full-load running current.

From the table below it will be gathered that the "commutator types" are all variable speed motors, the speed depending almost entirely upon the load for the time being, while they have good starting characteristics. The "induction" type, on the other hand, run at practically constant speed irrespective of load, that is to say, the speeds seldom drop more than 4 or 5 per cent. on full load, and never rise above synchronism when running unloaded. The starting effort of the plain split-phase motor, however, is not very great, and it is extravagant of starting current. By combining it with the repulsion or the capacitor method of starting, however, these drawbacks almost disappear.

Type of Motor	Speed	Starting Torque	Starting Current
		Per Cent.	Per Cent.
Universal A.C./D.C. commutator type	Variable with load	150/200 on A.C. 500/600 on D.C.	200/300 on A.C. 600/800 on D.C.
Repulsion Type (commutator A.C.)	Variable with load	150/200	200/300
Induction Type Split-phase start	Almost constant	180	500/600
Induction Type Repulsion start	Almost constant	300/350	350
Induction Type Capacitor start	Almost constant	300/350	400

Constructional Differences

Dealing first with the variable speed or "commutator type" of motor, these resemble very much the familiar direct current motor in their make-up, being provided with an ordinary wound armature and brush gear. In the "Universal" motor all details are identical whether

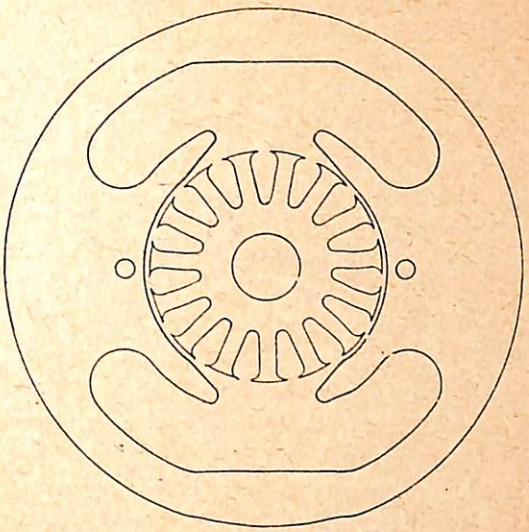

Fig. 2.—" Universal " type a.c./d.c. motor

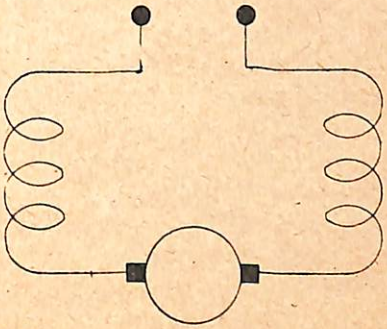

Fig. 3.—Connection scheme of universal motor

intended for use on direct or alternating current, as it is simply a series wound D.C. motor with the ordinary salient-pole laminated field magnet, the frame being illustrated in Fig. 2, and the connection scheme in Fig. 3.

Repulsion Motor

In the case of the " repulsion " type commutator motor, the wound armature is present, also the brushes, but the field may take the form shown in Fig. 4 with the coils distributed all round the periphery instead of being grouped on inwardly projecting poles. In this motor the brushes are short-circuited together, and the field or stator winding alone is connected to the line, as in Fig. 5.

Alternating current motors which fall into the " constant speed " class are all of the induction type, and correspond in their performance to the well-known shunt D.C. motor in that they have the same sort of speed variations on load. They do not maintain absolute constancy of speed, but are sufficiently near to make them more serviceable for work where the load varies considerably than the commutator type. Reference to the synchronous motor is omitted purposely, as they are scarcely a commercial proposition in such small sizes.

Induction Motor

The general appearance of the induction type motor, whatever the method of starting it may be, is evident from Fig. 6, and its connection scheme appears in Fig. 7. The rotor or armature consists of a series of solid copper bars threaded through the periphery of iron stampings and short-circuited at each end by heavy metal rings. Current is supplied to the stator winding only, there being no electrical connection between this and the rotor, in which current circulates by induction alone. The robust nature of the squirrel-cage type of rotor, and the absence of any commutator or brushes are very valuable features. Occasion-

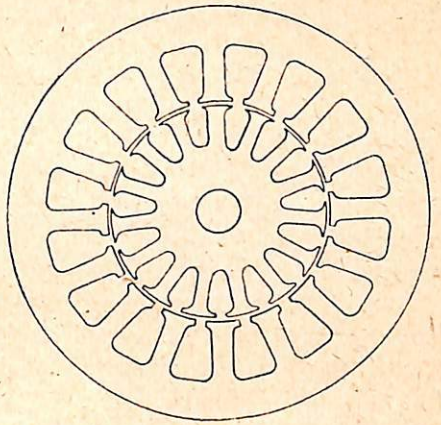

Fig. 4.—Repulsion type motor

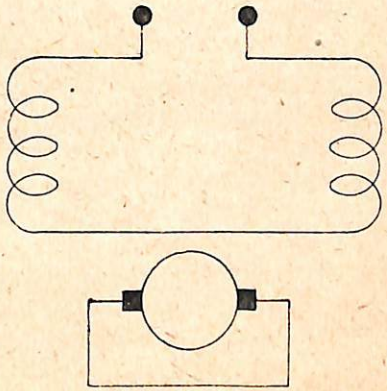

Fig. 5.—Connection scheme of repulsion motor

ally, instead of having a copper circuit in the rotor, aluminium bars and end rings are cast solid in one piece, thus avoiding any electrical joints. The stator is pierced with semi-enclosed slots all round the inner periphery, in which the exciting coils are grouped, which produce the required number of poles, both for the starting and the running windings.

Inverted-rotor Induction Motor

A variation of the squirrel-cage induction type motor is often encountered, in which the order of stator and rotor is reversed. This is called the " inverted-rotor " type, the stator or external member being the " squirrel-cage," and the rotor carrying a winding in slots. In this case, current has to be led into the rotor by means of brushes which bear on two slip rings. Fig. 8 shows the stator and rotor, and Fig. 9 the electrical circuit.

Capacitor Motor

The capacitor motor differs from the split-phase induction type only in the method of starting. There are two types of " capacitor " motors in use. One form employs a condenser in series with the usual starting coils, and is used for starting purposes only, both the starting winding and the condenser being open circuited by an automatic centrifugal switch when the motor is nearly up to speed. This is a type becoming very common in fractional horse power sizes below ½ H.P., and is known as the " capacitor-start " motor.

There is also another variation termed the " capacitor-start-run " motor, which employs a starting winding, a condenser, and a small auto-transformer, all connected as shown in Fig. 11.

The stator and squirrel-cage rotor is of the orthodox construction, and the stator has the usual starting winding displaced half a pole pitch, but instead of putting these two circuits in parallel only at the start, a combined unit

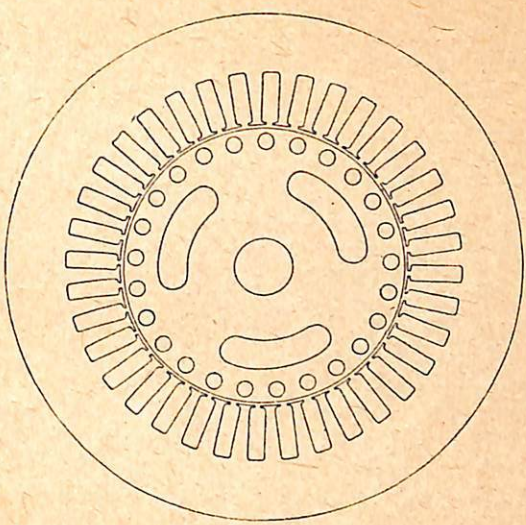

Fig. 6.—Induction type motor

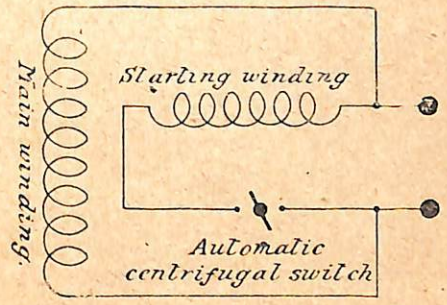

Fig. 7.—Connection scheme of induction motor

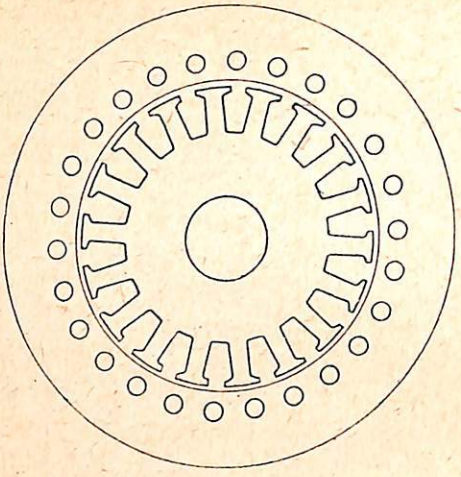

Fig. 8.—Induction type motor with inverted rotor

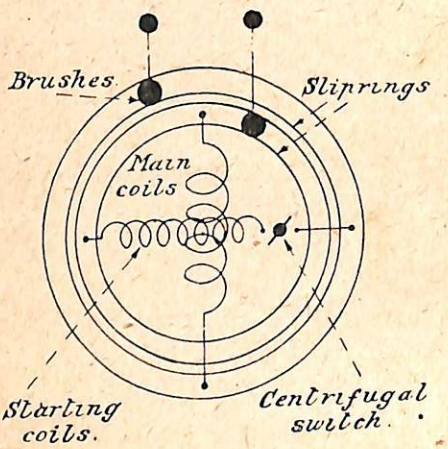

Fig. 9.—Connection scheme of inverted induction motor

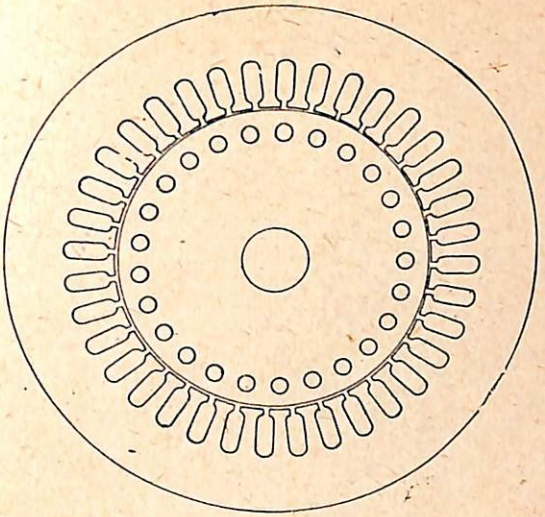

Fig. 10.—Capacitor-start type of induction motor

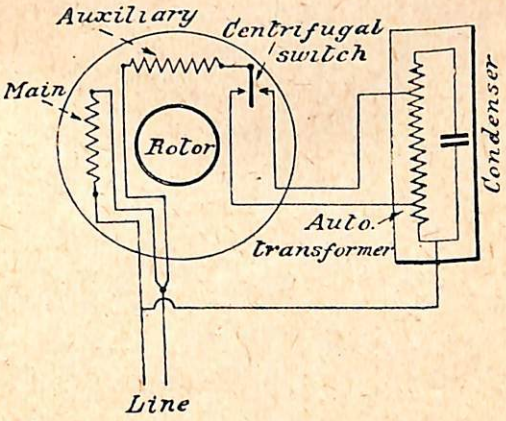

Fig. 11.—Connection scheme of capacitor-start-run motor

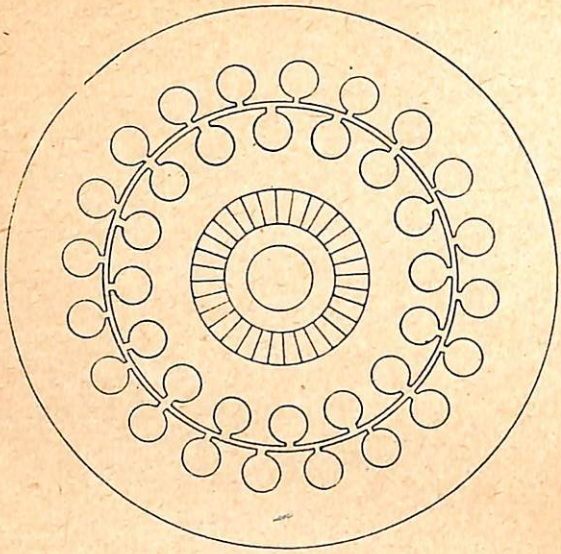

Fig. 12.—Repulsion-start type of induction motor

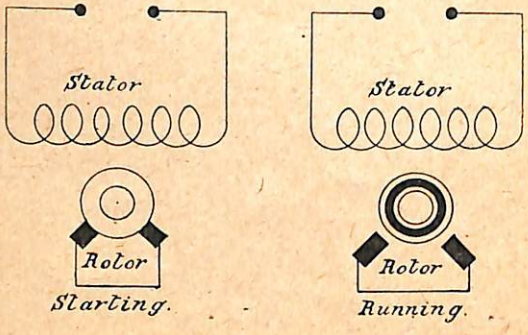

Fig. 13.—Connection scheme of repulsion induction motor

containing a condenser and small auto-transformer is connected in series with the starting winding and left permanently in circuit. The phase displacement so obtained enables the motor to start up as a two-phase motor and when speed is attained a centrifugal switch automatically changes the transformer tappings. Fig. 10 represents the frame, and Fig. 11 the electrical circuit.

Repulsion-start Induction Motor

The repulsion-start induction motor combines the ordinary stator with a wound armature and commutator in order to obtain the starting advantages of the repulsion motor. The motor starts as a repulsion motor, and at a critical speed a centrifugal device short-circuits the bars of the commutator together, converting it to a squirrel-cage rotor to all intents and purposes. At the same time the brushes are lifted off the commutator, so that any noise or wear and tear is eliminated. The frame is illustrated in Fig. 12, the electrical circuit in Fig. 13.

CHAPTER II

INTERNAL CONSTRUCTION

For those not accustomed to handle small motors very frequently, one of the quickest ways to recognise and distinguish between the types mentioned will be to refer to the photographs reproduced in this book.

Universal Motor

There will be no difficulty, for instance, in recognising the commutator type motor, whether it is of the " universal " or the " repulsion " type, and Fig. 14 shows the various parts in detail. The armature is of the familiar semi-enclosed skewed-slot form, bearing a commutator at one end and usually a ventilating fan at the other. The field magnet, shown midway between its two end frames, is of the laminated two-pole type, containing a single exciting coil on each of its salient poles. The brush gear, consisting of two spring-fed carbon brushes, appears inside the right-hand end frame. In the universal type of motor the fields and armature are in series with one another, and in series with the main terminals (see Fig. 3). To reverse the direction of rotation, interchange the internal connections between the field winding and the brush holders.

Repulsion Motor

There is practically no difference between the internal arrangements of universal and repulsion type motors, except

that in the latter the two brushes are short-circuited together and the field circuit alone connected to the line (Fig. 5). To change the direction of running in the case of the repulsion motor, it suffices simply to rock the brushes round into a new position, without altering any external or internal connections. This entails providing the motor with an adjustable brush rocker, and the positions for forward and reverse running are usually marked upon it.

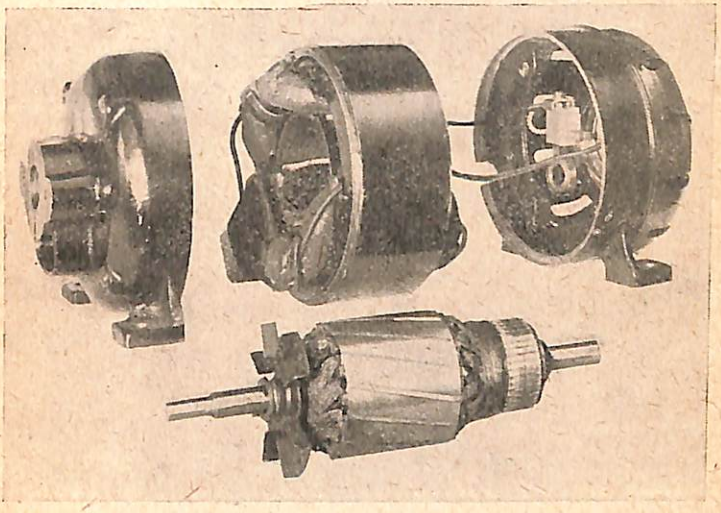

Fig. 14.—Component parts of universal motor

Commutator motors, whether of the series, universal, or repulsion type, are all self-starting, and require no special devices for "splitting the phase." Two and three phase motors are also self-starting, but single-phase motors of the induction type always require some means for accelerating them from standstill to running speed, and these devices will be explained as the motors come under review.

So far as starting gear of the hand-operated kind is concerned, it is very unusual to meet with this in connection

with such small sizes. Such gear as may be necessary is incorporated inside the motor, and is entirely automatic, so that the motors can be switched straight on to the line.

Split-phase-start Induction Motor

This motor, which for many years was the only available type before improved methods of starting were developed, is made in two forms, one with the slotted wound stator as the external member, and one with a squirrel-cage type of external stator. These will be found illustrated in Figs. 6 and 8. The photograph, Fig. 15, of the interior represents the squirrel-cage stator type, and shows well the component parts. As the stator is practically solid with no windings on it, it will be appreciated how well adapted it is to meet service of a very exacting nature. The wound rotor with its collector rings on the left-hand end and its disc fan on the right has two windings, one set constituting the main running coils and the other the starting coils, the latter being displaced half a pole pitch from the main running coils. An internal centrifugal switch, of a type which will be shown in a later photograph, automatically interrupts the starting coil circuit when the rotor has run up to nearly synchronous speed. The terminal box, containing two carbon brushes which make contact with the slip rings, will be seen just below the rotor. Reversal of rotation is effected by changing over the ends of either the main or the auxiliary coils where they join with the other set of windings. The devices used for automatically interrupting the starting coil circuit are many and various, and it would be impossible to illustrate them all. In most cases their operation is very obvious. External starting is seldom resorted to, but it can be accomplished by the use of a "Twinob" switch operated by hand. Fig. 16 is a circuit diagram of a hand-operated starting switch. The weak point about hand-operated starting is that it introduces a risk of the windings being burnt out if operated too rapidly, whereas

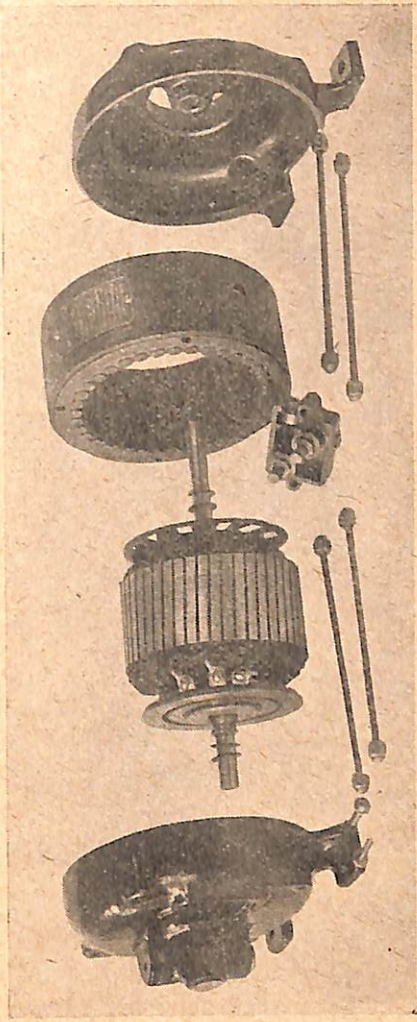

Fig. 15.—Component parts of induction motor with inverted rotor

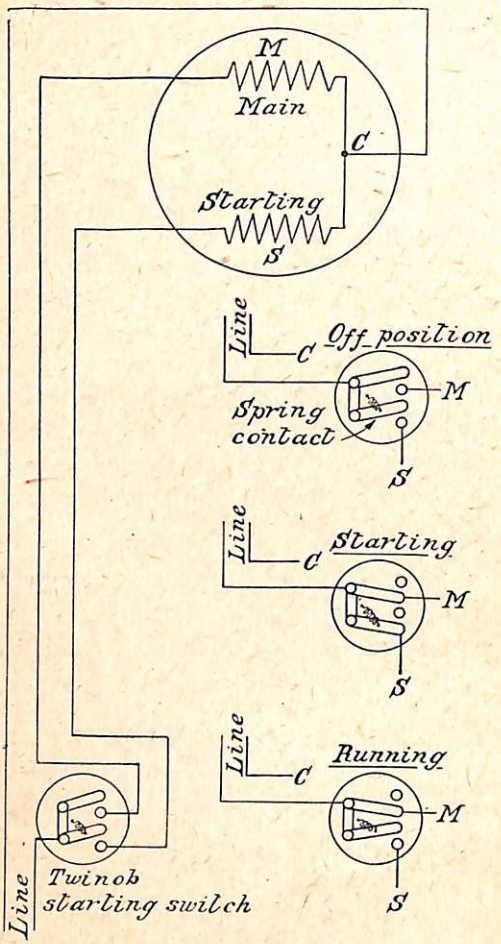

Fig. 16.—Circuit for external hand-operated starting switch

the automatic switch cannot come into operation until the motor has had time to attain its proper speed.

Repulsion-start Induction Motor

Fig. 17 will serve to illustrate the assembled position of the commutator, brushes, short-circuiting disc, and brush-raising gear in this class of motor. The component parts are presented in the opened-up view of this motor, Fig. 18, which shows well the arrangement of coils on the stator, the wound rotor with its fan, and the holes pierced in the blades of the latter for purposes of balancing. An enlarged view of the wound rotor will be given in Fig. 19, to show the means by which the windings on the rotor are converted into a squirrel-cage, by short-circuiting the commutator bars together when speed has been attained. On the left-hand end of the shaft is a sliding cup which moves along the shaft as its internal weights fly out under centrifugal action, and in doing so, presses a disc against the ends of the commutator bars. A shaped cam plate inside the cup, fixed to the shaft, retains the weights, and is so shaped as to wedge the cup inwards against the tension of a spring as the weights travel outwards. As the sliding cup moves towards the commutator, it engages with two triggers seen in Fig. 17, which in turn lift the brushes from the commutator, where they are no longer required when at full speed.

Fig. 22 is a sectional view of the short-circuiting and brush-lifting gear employed in the repulsion-start type of induction motor.

The repulsion-start type of motor has a considerable advantage over split-phase starting methods, where a high starting effort is required, but it is relatively a little more complicated and expensive. Consequently, the simpler and cheaper type of motor is still a favourite.

The Centrifugal Switch

As already stated, starting devices for split-phase motors are very numerous ; one very popular and reliable form used

with wound rotors is that shown in Figs. 20 and 21. This is a wound rotor such as is employed with the inverted squirrel-cage machine, the end and side views being exhibited separately.

Capacitor Induction Motor

So far as the running operation of this motor is concerned it presents no unusual features. The assembly consists of

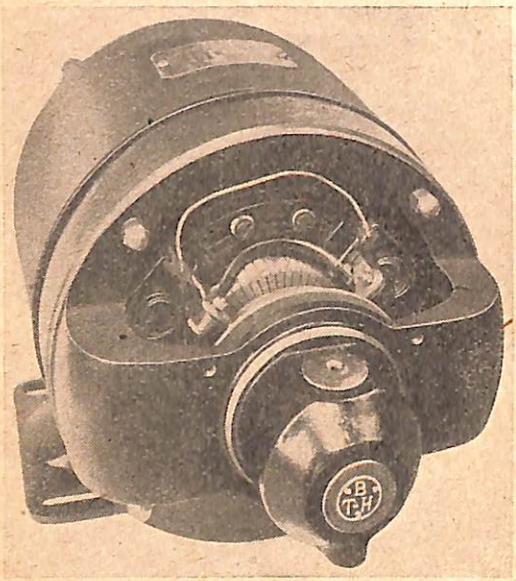

Fig. 17.—Repulsion-start induction motor assembled

the usual stator with semi-enclosed slots round the inside edge of its periphery, associated with an ordinary squirrel-cage type of rotor seen in Fig. 6. The means of starting, however, are quite a recent development and differ from anything else yet presented. As is well known, the necessary starting effort with single-phase motors is secured by splitting the phase, that is, by providing an auxiliary set of

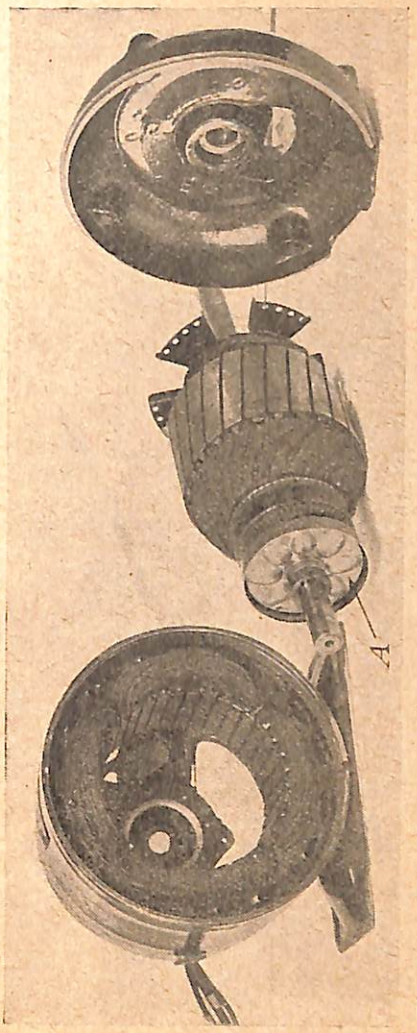

Fig. 18.—Component parts of repulsion induction motor. (A) Cam plate, containing shaped recesses for guiding weights. Control spring is inside, next to commutator

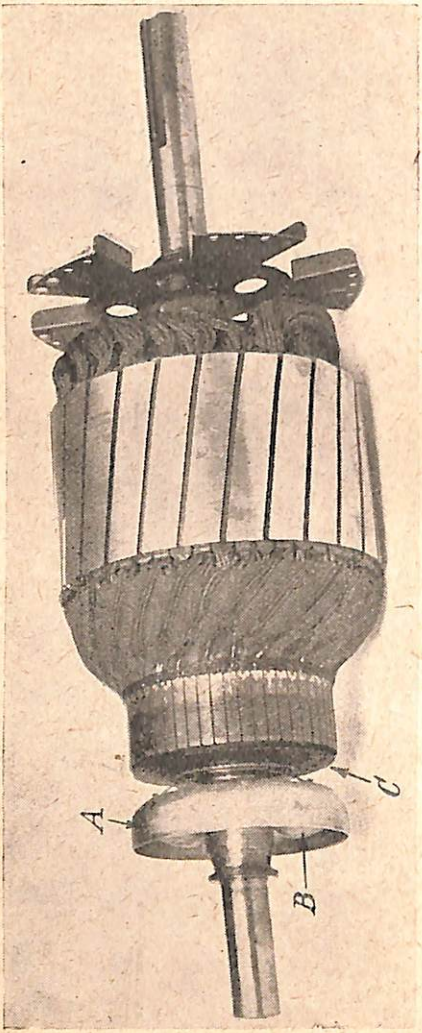

Fig. 19.—Rotor of a repulsion induction motor. (A) Sliding cup, moving along shaft when weights fly out under centrifugal action. (B) Cam plate, retaining weights in place. (C) Disc for short-circuiting commutator

coils which produce secondary poles midway between the main poles, so designed as to come into operation either earlier or later than the main poles. This phase-lag creates a sliding field which drags the rotor round in a definite direction, and can be brought about by varying the relative inductances of the main and starting coils, so that current does not arrive at the maximum strength in the two sets of

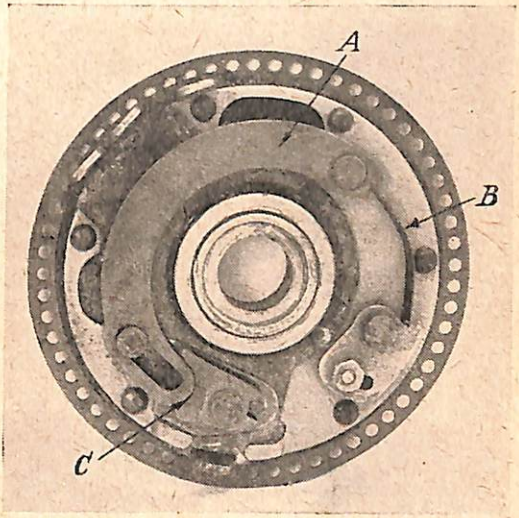

Fig. 20.—End view of internal centrifugal switch. (A) Pivoted weight arm, moving outwards under centrifugal action. (B) Control spring. (C) Contact

coils at identical instants. By introducing a condenser in series with the starting coils, the current in this circuit leads in phase, and the power factor of the motor as a whole is improved, so that it possesses distinct running advantages. Its construction, however, may be a little more complicated, since in order to obtain the best performance possible, an auto-transformer as well as a condenser is found desirable, together with an automatic centrifugal switch to make the

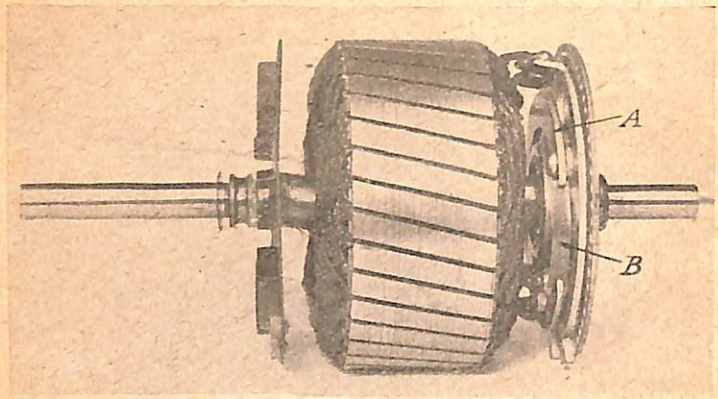

Fig. 21.—Side view of internal centrifugal switch. (A) Pivoted weight arm. (B) Control spring

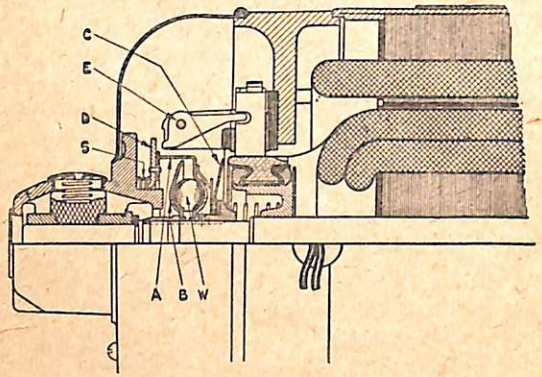

Fig. 22.—Sectional view of B.T.-H. repulsion-start induction motor, showing commutator and brush gear. (A) Cup containing weights W. (B) Cam plate. (C) Short-circuiting disc. (D) Sliding plate. (E) Small cranked levers which lift brushes. (S) Spring

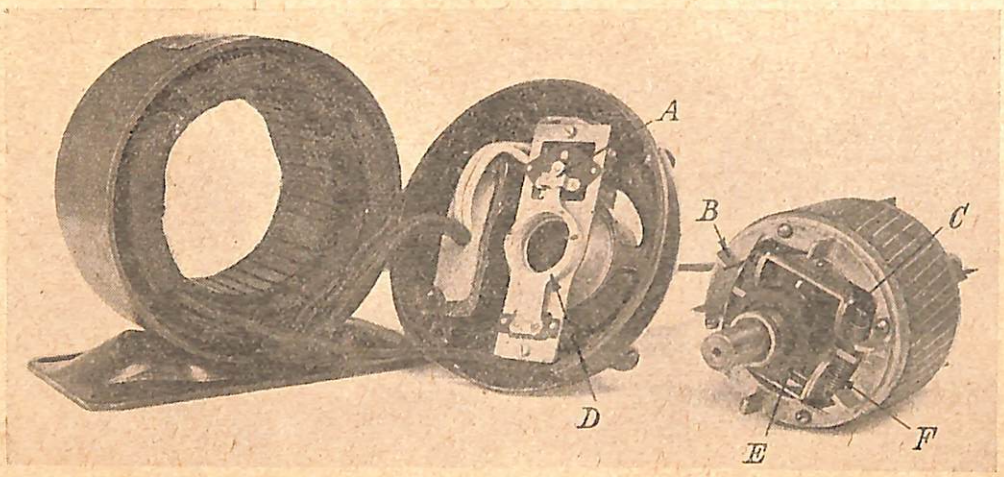

Fig. 23.—Component parts of capacitor motor. (A) Contacts. (B) Fan blades. (C) Pivoted weights. (D) Spring-carrying contacts. (E) Sleeve, sliding back on shaft when pivoted weights fly out. (F) Control springs for pivoted weights

necessary changes in the tappings as the motor speeds up. The transformer can be housed inside the frame in small machines, but the condenser generally requires to be a separate unit, or at least fixed to the motor externally. Fig. 23 is a view of the interior of a " capacitor-start-run " B.T.-H. motor, showing the disposition of the parts. The contacts in the transformer circuit shown inside the end frame are operated by a sliding collar on the shaft, which itself is brought into action by hinged spring-controlled

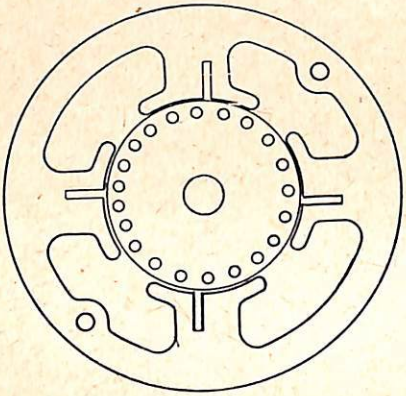

Fig. 24.—Shaded-pole induction motor

weights. Motors constructed on these lines are virtually two-phase motors, since both main and auxiliary windings are left in circuit the whole time. Owing to their high power-factor and higher efficiency, the full load current for a given power output is less than any of the previous types, hence the percentage starting-current is actually somewhat lower than the figure given in the previous table on page 10.

Shaded-pole Induction Motors

These are confined to quite small sizes, where a very weak starting torque suffices, such as in the case of ventilating fans. They invariably have stators of the " salient-pole "

type, and are generally multipolar for slow speed running. Each pole is provided with a slot on one side of the pole piece, in which is embedded an endless copper band. The effect is to produce a small time-lag between the magnetisation of the polar face as a whole and that portion of it embraced by the "lag-loop," resulting in a sliding flux across the pole face, which exerts a corresponding drag upon the squirrel-cage rotor. Fig. 24 shows the usual type of frame.

From this series of photographs showing the interim arrangements, and the explanatory notes given, there should not be much difficulty now in finding the particular class to which any motor belongs, the nature of its starting torque, and the details of its starting gear.

CHAPTER III

ESTIMATION OF NEW WINDINGS

CONSIDERABLE interest centres around questions of rewinding or repairing electrical defects, and requests are frequently made for simple rules by means of which suitable windings can be calculated to meet any specified voltage, frequency and speed. Data for the calculation of direct current generators and motor windings abound in almost every electrical handbook, but the scarcity of similar information regarding alternating current motors is rather striking.

It is not a subject, unfortunately, that can be treated with great precision in a simple way. There is no particular mystery attached to it, but it can hardly be gone into thoroughly unless the reader is conversant with vectorial quantities and mathematics on a somewhat higher plane than appeals to the general reader.

So far as the present notes are concerned, this need not constitute any great drawback, since we are not really concerned with the actual design or the predetermination of performance. The model maker, with a motor of fixed dimensions already in his possession, only needs some simple formula that will guide him as to the quantity and size of wire to employ, and the arrangement of the coils in the correct way to get the desired results. He has not to work to a rigid specification, where questions of efficiency, power factor, and temperature arise, and must be adhered to, on enalty of the motor being rejected. Such matters as these

lie within the province of the specialist, and even then are arrived at very frequently more by trial than by actual calculation when such small power units are in question. All that the average worker wants is a winding that he can feel reasonably confident will give him a respectable performance and useful service, not necessarily one that exhibits superior points in competition with the productions of some rival manufacturer.

Modifying Existing Windings

If the windings of the motor to be repaired have not been completely burned out and the coils destroyed, it is a fairly straightforward matter to modify any existing winding in order to suit another circuit of different voltage or frequency, provided the same number of poles are retained in the new winding. It needs care, of course, in stripping off the old coils to make sure that the turns are counted correctly and the gauge of wire properly checked up, but once this is done the rest is a matter of simple arithmetic.

Turns and Voltage

Other things being equal, the turns are directly proportional to the voltage, so that when changing from one voltage to another, the turns on the old winding will be increased or decreased in simple proportion. For example, if there are 50 turns per coil on the stator winding of a 200-volt 50-cycle motor, and it is required to modify the winding to run on a 240-volt 50-cycle circuit, the coils will be modified in the same proportion, namely :—

$$50 \times \frac{240 \text{ volts}}{200 \text{ volts}} = 60 \text{ turns.}$$

Turns and Frequency

If a 200-volt 40-cycle motor having 38 turns per coil is required to run on another 200-volt circuit, but of 60 cycles instead of 40, the turns required will be varied in inverse

proportion, that is to say, the higher the frequency the fewer the turns. For instance :—

$$38 \times \frac{40 \text{ cycles}}{60 \text{ cycles}} = 25 \text{ turns approximately.}$$

When the alteration in frequency is considerable, such as changes in the order of 2 to 1 or more, a better rule to use is to modify the turns in inverse proportion to the square roots of the respective frequencies, otherwise there may be some tendency to overheating on the higher frequencies.

Combined Voltage and Frequency Modifications

When both the voltage and the frequency have to be varied, first modify the turns to suit the changed voltage, and then correct the figure so obtained by again modifying to suit the frequency. A 200-volt 60-cycle motor, for instance, with 40 turns per coil, when changed to a 220-volt 50-cycle circuit would need the coils adjusted as follows :—

$$40 \times \frac{220 \text{ volts}}{200 \text{ volts}} = 44 \text{ turns for corrected voltage,}$$

and

$$44 \times \frac{60 \text{ cycles}}{50 \text{ cycles}} = 53 \text{ turns approximately for corrected frequency.}$$

Speeds will vary, of course, according to frequency changes, but not with voltage changes. The gauge of wire may also need modification when changing from one voltage to another, and this will be explained later.

Generally, the same winding will serve for voltage ranges between 200 and 220, or 230 to 250 volts, provided the frequency is unaltered. Also the same winding is often used for frequencies varying between 40 and 60 cycles, although this is not always advisable. It is also worth while noting that most induction motors can be used on two different voltages if the stator winding is divided at the half-way point, so that the two halves can be put either in

series or in parallel. This enables one winding to be used for either 100 or 200 volts, or 110 and 220 volts, according to the manner of coupling up the stator coils. Another interesting point is that since turns and voltage vary in direct proportion, while turns and frequency vary almost in inverse proportion (see preceding rule), the same winding may be used on a circuit of twice the frequency if the voltage is twice as high. A 110-volt 50-cycle motor, for instance, would run on 220 volts 100 cycles without any change in winding. The speed, however, would naturally be twice as great in the latter case.

Required Working Conditions

When rewinding, the very first point to settle upon is the performance required from a motor, in other words its "rating" in (*a*) horse power; (*b*) voltage; (*c*) frequency; and (*d*) speed. Most commercial motors already have this information on a plate fixed to the frame, so that it only remains to settle upon a winding that will suit the voltage and frequency of the circuit, and then arrange the coils in such a way as to obtain the desired speed.

Relieved of all responsibility as regards size and design, the calculations can be taken in the following order:—

1. Size of wire.
2. Total number of turns.
3. Number of poles.
4. Coils per pole.
5. Coil grouping.

Calculating Wire Sizes

All the rules given hereafter must be understood as practical approximations, which, while giving a serviceable result, are not necessarily the very best possible, since it is our purpose to avoid elaborate calculations. After estimating the first winding by this means, it may be found that the results obtained on a running test, perhaps, give indications

where the specification may be improved upon when the occasion next comes round for a further rewind.

In settling the size of wire to be used, there are three factors to take into account : The first is the horse power or "watts output" (1 H.P. = 746 watts) ; the second is the voltage of the supply ; while the third is the efficiency or "watts input." Small motors naturally have not such a good efficiency as larger ones, a greater proportion of the input watts being wasted in iron and copper losses than is the case with their larger brethren. A conservative but reasonable scale of efficiencies for D.C. and A.C. motors of sizes under 1 H.P. might be safely taken roughly as under :—

$\frac{1}{16}$ to $\frac{1}{10}$ H.P. - - -	45 per cent.
$\frac{1}{8}$ to $\frac{1}{6}$ H.P. - - -	50 per cent.
$\frac{1}{4}$ to $\frac{1}{2}$ H.P. - - -	60 per cent.
$\frac{3}{4}$ to 1 H.P. - - -	70 per cent.

The efficiencies of A.C. motors, especially those designed for low speeds, will tend to be somewhat lower than these figures, which must be used, therefore, with discretion.

Since 1 H.P. = 746 watts, the actual input watts required to produce any of the above outputs would be approximately :—

For $\frac{1}{16}$ H.P. $\quad \frac{746}{16} \times \frac{100}{45} = 103$ watts.

For $\frac{1}{10}$ H.P. $\quad \frac{746}{10} \times \frac{100}{45} = 170$ watts.

For $\frac{1}{8}$ H.P. $\quad \frac{746}{8} \times \frac{100}{50} = 186$ watts.

For $\frac{1}{6}$ H.P. $\quad \frac{746}{6} \times \frac{100}{50} = 248$ watts.

For $\frac{1}{4}$ H.P. $\quad \frac{746}{4} \times \frac{100}{60} = 310$ watts.

For $\frac{1}{2}$ H.P. $\quad \frac{746}{2} \times \frac{100}{60} = 620$ watts.

$$\text{For } \tfrac{3}{4} \text{ H.P.} \quad \frac{746 \times 3}{4} \times \frac{100}{70} = 800 \text{ watts.}$$

$$\text{For 1 H.P.} \quad \frac{746}{1} \times \frac{100}{70} = 1{,}066 \text{ watts}$$

The above figures will require a certain modification to allow for "power factor," since there is a phase difference between the volts and the amperes in A.C. motors, a point that will be explained farther on. For D.C. motors no modification is needed.

The current required for any size of motor in the above list can now be arrived at in two stages. First, the input watts for a given size and efficiency are divided by the terminal voltage, and the result so obtained corrected according to the power factor if it is for operation on A.C. For instance, a 230-volt $\frac{1}{4}$ H.P. D.C. motor will take a current of

$$\frac{310 \text{ watts}}{230 \text{ volts}} = 1.35 \text{ amperes, nearly.}$$

A $\frac{1}{10}$ H.P. 110-volt motor would require a current of

$$\frac{170 \text{ watts}}{110 \text{ volts}} = 1.55 \text{ amperes, and so on.}$$

But the actual current in the case of A.C. motors is a little in excess of the calculated figures, because such motors have a power factor that is less than "unity," which means, in plain language, that the alternations of current and E.M.F. are not exactly in step with one another, and do not arrive at their maximum values in each wave at the same instant. The consequence is that the watts, instead of being the product of the full volts × amperes, are something less. To put it in another way, the "true effective watts" are less than the "volt-ampere" values. Taking an all-round power factor of 0.6 to 0.7 for small A.C. motors, this will now increase the first estimation of current by an amount which is found by dividing the estimated figure by, say, 0.7, as we shall see in a further example.

Since the size of wire to be used for the winding is naturally determined by the current it has to carry, it becomes easy to select a suitable gauge once this current has been ascertained. Taking an all-round current density of 3,000 amperes per square inch cross-section of copper as an approximate figure for small motors in general, subject to some little latitude where ventilation is either unusually restricted or else exceptionally good, a suitable gauge of wire for the calculated current is quickly ascertained by reference to the following table :—

WIRE GAUGES SUITABLE FOR SMALL A.C. AND D.C. MOTOR WINDINGS

S.W.G.	Current	S.W.G.	Current	S.W.G.	Current
40	0.054	32	0.274	24	1.140
39	0.063	31	0.315	23	1.356
38	0.084	30	0.362	22	1.848
37	0.108	29	0.429	21	2.412
36	0.136	28	0.516	20	3.064
35	0.165	27	0.633	19	3.771
34	0.199	26	0.762	18	5.43
33	0.234	25	0.942	17	7.389

Calculation of Turns

The next stage is to decide on the number of turns, and this is not quite so easy to arrive at if the original winding has been entirely lost sight of. In many cases it will be possible to unwind and count the turns of the previous winding, but the motor may have been already stripped down or the coils so badly damaged that no definite information can be gathered from them. Bearing in mind that the object is to arrive at a useful figure in the easiest possible way, we will see what the fundamental formula relating voltage to flux and speed will do for us. This in its simple form, expressed as C.G.S. units, is :—

E (electromotive force) = L (length of wire)
× H (magnetic strength) × V (velocity)

The velocity V is one either of rotation or of flux reversals. The magnetic strength H is the total number of lines of force that pass through the air gap and are cut by the revolving rotor or are linked up with the stator turns.

Whether the motor is for direct or alternating current makes no difference to the relationships expressed above, as the velocity or speed component may be either one of rotation in a field of fixed value, or the flux itself may change at a definite rate so many times per second, the result in either case being to induce an E.M.F. in the turns of wire affected by it.

The problem is best dealt with by assuming at the outset that our motor is a dynamo, and that the turns of wire on it have to generate an E.M.F. of the same voltage as that of the circuit upon which the motor is to run, when the magnetic field is pulsating at a rate dependent upon the frequency of the supply. Since the frequency or cycles per second means four changes with every wave, that is growth to a maximum and decline to zero value first in one direction and then in the other to complete one cycle, the speed or velocity component will be four times the frequency, and if we know the required voltage and frequency and the total magnetic flux, the necessary turns can be ascertained by the simple expression :—

$$\text{Turns} = \frac{\text{Volts of supply} \times 10^8}{(\text{Supply frequency} \times 4) \times \text{Flux per pole}}$$

It is true that we are taking liberties somewhat with orthodox formulae, but our mathematical readers must excuse this with the object of attaining utmost simplicity.

The calculation of turns is fairly easy if carried out on these lines, because we can get all the figures in this formula except the flux from circuit conditions already known, while the flux itself can be arrived at from actual measurement of the stator dimensions and a knowledge of the permissible magnetic flux density per square inch in the air gap.

Calculating Value of Magnetic Flux

In order to find the only remaining unknown quantity in the above equation, namely, the flux, the simplest way is to proceed along the following lines :—

Study the diagram in Fig. 25, which represents an ordinary stator stamping with the lines of magnetic force or " flux " drawn in as they would appear in the case of a two-pole

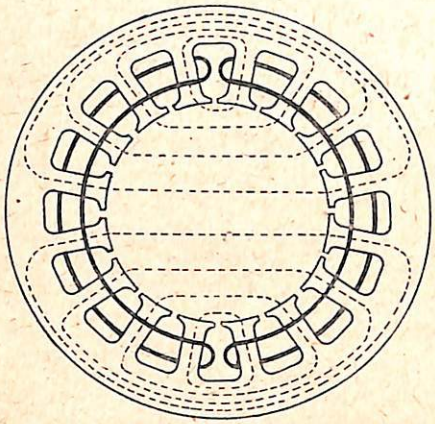

Fig. 25.—Flux distribution in stator of two-pole induction motor

winding. Beside the flux, which is indicated by dotted lines, will be seen two other full lines at right angles, which represent the magnetising coils on the stator which set up this flux. It is the interlinking of the pulsating magnetic circuit with these coils which sets up the reactive voltage in just the same way as in the static transformer. As the flux crosses the air gap twice in order to complete its circuit, the whole of the flux lines pass into one half of the air gap and out of the other half on their return journey, and it should be realised that the total number of lines will not be greatly affected whether the stator is wound for two, four, or more poles, since it does not affect the area of the air gap through which they pass, but merely their respective directions.

This gives us an easy method of determining the value of the total flux in any motor of known dimensions, by first finding the length of the inner circumference of the stator bore and multiplying this by its depth in inches. This gives a figure representing the total area of the stator pole faces in square inches, the flux emerging from one half and returning by way of the other half, so that half this total area forms the pole section, as a preliminary calculation. But this figure needs a correction, because the whole of the polar faces do not consist of iron, but the iron teeth in the stator alternate with air spaces in which the coils are wound. For magnetic purposes, therefore, the calculated area is reduced in proportion to the comparative widths of iron teeth and air spaces. For general purposes we can call this factor 0.5, in other words, we assume the teeth to be the same width as the slots.

The only other information required now to arrive at the total flux is the magnetic density in lines per square inch. Here there must always be a certain amount of latitude, since small motors cannot be worked to so high a flux density as large ones, but for fractional horse power sizes the all-round figure of 30,000 lines per square inch will not be far from the usual practice. This value, multiplied by the net area per pole, as calculated above, will give the remaining value wanted to complete our estimation of the total turns of wire that will be required.

Speed Calculations

With all induction motors the speed is a function of the frequency of the supply current, taken in conjunction with the number of poles on the stator winding. If the supply current alternates 50 times a second, that is 3,000 times a minute, this will also be the speed of the motor if the stator is wound with two poles. With four poles the speed would be 1,500 r.p.m., and with six poles 1,000 r.p.m.

In order to find the number of pairs of poles to give to the

stator winding, divide the frequency per minute by the required speed in revolutions per minute. Thus, for 1,800 r.p.m. on a 60-cycle circuit (3,600 cycles per min.) :—

$$\frac{3600}{1800} = 2 \text{ pairs of poles, or a "four-pole" winding.}$$

Likewise to get 1,500 r.p.m. on a 50-cycle circuit :—

$$50 \text{ cycles} \times 60 \text{ seconds} = \frac{3000 \text{ cycles per min.}}{1500 \text{ r.p.m.}}$$

$= 2$ pairs of poles, which is again a four-pole winding.

Do not waste time in trying to get intermediate speeds for it cannot be done with this class of motor ; the speeds of induction motors have always a definite whole-number ratio to the frequency, subject, of course, to the small speed drop on load called "slip," which usually does not amount to more than 4 or 5 per cent. of the unloaded speeds.

Calculating the Stator Windings

A worked-out example will be the best method of illustrating the process. It will be assumed that there is a ¼-H.P. induction motor with a squirrel-cage rotor and split-phase starting winding, to be rewound to run on a 220-volt 50-cycle single-phase circuit at a speed of 1,400 to 1,500 r.p.m. Suppose all trace of the previous winding to be lost, and nothing but the bare particulars on the rating plate to serve as a guide to output, so that the novice is thrown on his own resources entirely as to the new winding.

The first thing to do is to find the current consumption. According to the tables previously given, the input watts at full load for a motor of this size should be about 310 watts ; full load current is found by dividing the watts input by the circuit voltage, and then correcting for power factor :—

$$\frac{310 \text{ input watts}}{220 \text{ volts}} = 1.4 \text{ amperes.}$$

Taking power factor as 0.7, $\frac{1.4 \text{ amperes}}{0.7} = 2.0$ amperes

as the actual current consumption in the main running coils, ignoring for the moment any question as to starting coils. Refer next to the wire table and it will be found that a No. 21 S.W.G. wire can be safely used, as it is advisable to choose the heavier gauge when the figure comes between two.

The gauge of wire and the number of poles for our main stator winding is now established, and the estimation of total turns necessary can be tackled.

Carefully measure up the bore of the stator and its length. Taking an average size of motor for this rating, we will assume the stator to have a bore of $3\frac{1}{2}$ in. diameter and a depth of 2 in. The length of the bore circumference is therefore 11 in. and the depth 2 in., that is a total of 22 sq. in. to be shared between the outgoing and incoming flux lines. Our magnetic pole section is therefore 11 sq. in. multiplied by the factor 0.5 to correct for loss of iron due to the slot spaces, or a working value of 5.5 sq. in. over the whole of the stator bore divided by the number of poles required.

Taking a flux density of 30,000 lines per square inch as a practical working figure for small induction motors, the total flux per pole would therefore work out as follows :—

$$\frac{5.5 \times 30000}{2} = 82{,}500 \text{ lines per pole for a two-pole stator.}$$

$$\frac{5.5 \times 30000}{4} = 41{,}250 \text{ lines per pole for a four-pole stator.}$$

$$\frac{5.5 \times 30000}{6} = 27{,}500 \text{ lines per pole for a six-pole stator.}$$

For general use 30,000 lines per square inch is a safe figure to employ.

The formula for ascertaining turns can now be applied, remembering that the reactance volts for a given frequency will be proportional to the turns in each pole-group of windings and the flux carried by that pole. If, for instance, it is to be a two-pole winding with all the pole groups connected in series, each group of coils forming one pole

must give a reactance of $\frac{220 \text{ volts}}{2 \text{ poles}} = 110$ volts per pole, when interlinked with one-half of the total flux. If it is a four-pole stator, each pole group must give a reactance of $\frac{220 \text{ volts}}{4 \text{ poles}} = 55$ volts, when interlinked with one-quarter of the total flux, and so on.

From this, the value of turns required for a two-pole winding :—

$$\text{Turns} = \frac{220}{2} \times \frac{100{,}000{,}000}{50 \times 4 \times 82500} = 660$$

With a four-pole winding the number of turns will be

$$\frac{220}{4} \times \frac{100{,}000{,}000}{50 \times 4 \times 41250} = 660$$

It is a significant fact that the number of turns remains the same, whatever may be the number of poles on the stator. At first sight it would appear to be impossible to find room for the increase in the total turns with the addition of each pair of poles, but in practice this is met by a corresponding reduction in the size of the wire used, enabling more turns to be got into the same space. This is practicable for the reason that with every additional pair of poles the speed of the motor is reduced in proportion, and consequently the horse power that it can develop. Reduced output calls for reduced input in the way of smaller currents which can be carried by wires of a smaller area.

The stator we are now considering, we will say, has twenty-four slots, and with one coil per slot there will be twelve coils, since each coil has two sides and occupies two slots. Each of the twelve coils, therefore, requires

$$\frac{660 \text{ total turns}}{12 \text{ coils}} = 55 \text{ turns per coil,}$$

the nearest whole number being sufficiently accurate.

These twelve coils will be equally divided between the four stator poles, that is, three coils per pole, and the

grouping will be concentric, one inside the other, as in Fig. 26.

All coils are in series, and the connections between adjacent groups of coils must be such that they are polarised alternately north and south in sequence.

Starting Coils

There is considerable latitude permissible with these, and there is no necessity to indulge in any calculations unless a

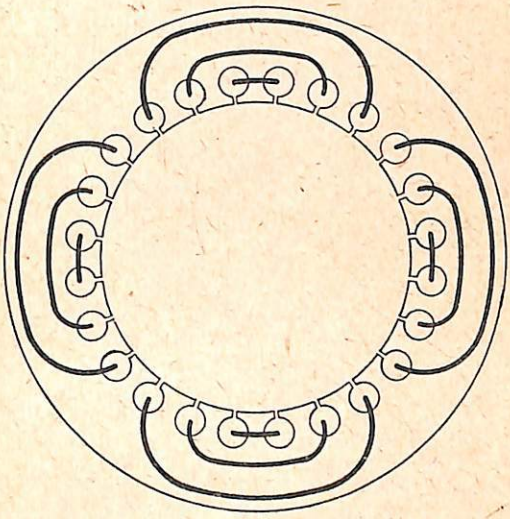

Fig. 26.—Coil-grouping on a four-pole stator

definite starting torque is essential. For general purposes a simple rule is to make the starting winding of the same number of coils as the main winding, but each coil to have half the turns and to use wire of six gauges smaller. They are wound over the main coils, but their angular position on the stator is exactly half-way between the groups of main coils, that is, they are displaced half a pole pitch so that they may be equally effective for starting purposes whichever way the motor runs.

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